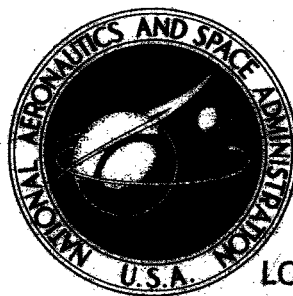


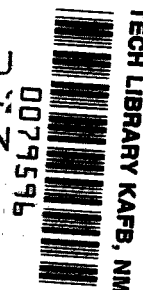
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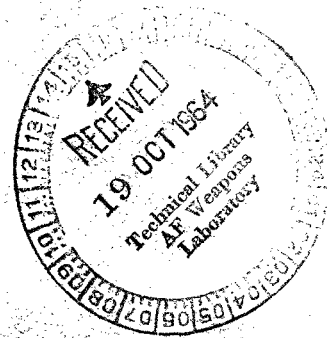
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AN INVESTIGATION OF THE DYNAMIC STABILITY AND CONTROL CHARACTERISTICS FOR A TRANSPORT CRUISING AT A MACH NUMBER OF 3

by Lawrence W. Brown
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Page 17: The value of C_{l_p} (tenth item of table I) should have a minus sign added.
Thus,

C_{l_p} -0.124



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
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SUMMARY

A theoretical investigation has been made of the characteristic modes of the dynamic lateral stability of a supersonic-transport configuration, cruising at a Mach number of 3 at altitudes of 60,000 feet and 70,000 feet with trim angles of attack of 3.6° and 5.8° , respectively. The stability and flying qualities were studied by using the classical linearized equations of lateral motion, the ratio of the roll angle to the equivalent side velocity, and the ratio of the roll angle to sideslip. The effects of the cross-control derivatives on the stability of the configuration with damper augmentation were investigated. In addition, the roll coupling of the unaugmented configuration was considered.

Results show that the interaction of the roll and yaw dampers and the change in stability with altitude require a system with variable damper gains to obtain satisfactory lateral stability. In addition, too small a value of the static directional derivative may cause large roll-to-sideslip ratios and roll-coupling problems.

INTRODUCTION

An investigation of possible configurations for the supersonic commercial transport has been in progress at the National Aeronautics and Space Administration. This aircraft will extend commercial flights to Mach numbers of 3 and to altitudes as high as 70,000 feet. Considerable attention has been given to many different design concepts to develop a superior cruise vehicle. Since no generally accepted flying-qualities requirements exist for the lateral modes of transport type of aircraft, the stability characteristics presented herein are compared with existing military specifications for lateral directional stability. Preliminary estimates of the handling qualities determined from simulator studies reported in reference 1 indicate the necessity for further investigation of the configurations considered.

A theoretical investigation was undertaken of the lateral stability characteristics of a supersonic-transport configuration incorporating variable-sweep wings for which the sweep varies with speed and altitude until it reaches 75° for a cruising speed of a Mach number of 3. This analysis contains calculations of the dynamic lateral-stability characteristics for altitudes of 60,000 feet and 70,000 feet and a gross weight of 375,000 pounds for the configuration with 75° sweepback at a Mach number of 3. Various yaw- and roll-damper combinations are considered. In these cases, the effects of omitting or including the cross-control derivatives were studied.

The results are presented as plots of the reciprocal of the time to damp to half-amplitude of the lateral modes with increasing damper gains and angle of attack. The Dutch roll damping of the aircraft augmented with dampers is presented as a function of the ratio of roll angle to equivalent side velocity and is compared with the flying-qualities criteria. The critical roll velocity for inertial coupling of the undamped aircraft is also presented.

SYMBOLS

b	wing span, ft
\bar{c}	wing mean aerodynamic chord, ft
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
C_l	rolling-moment coefficient, $\frac{\text{Rolling moment}}{qSb}$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
C_{mC_L}	static margin, $\frac{dC_m}{dC_L}$
C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{qSb}$
C_y	side-force coefficient, $\frac{\text{Side force}}{qS}$
$C_{1/2}$	cycles to damp to half-amplitude
g	acceleration due to gravity, 32.2 ft/sec^2
h	altitude, ft
I_x, I_y, I_z	moment of inertia about the principal body axes, (slugs)(sq ft)

k_1	roll-damper gain, $\delta_a/\dot{\phi}$
k_2	yaw-damper gain, $\delta_r/\dot{\psi}$
M	Mach number
m	mass, slugs
p	rolling angular velocity
P	period
q	dynamic pressure, $\frac{\rho V^2}{2}$, lb/sq ft
r	yawing velocity
S	wing area, sq ft
$t_{1/2}$	time to damp to half-amplitude, sec
t_2	time to double amplitude, sec
V	velocity, ft/sec
v	side velocity, $\frac{\beta V}{57.3}$, ft/sec
v_e	equivalent side velocity, $v\sqrt{\sigma}$, ft/sec
x_{cg}	center-of-gravity position measured from wing pivot point, aft direction being positive, ft
α	angle of attack, degrees, except in appendix where α is in radians
β	angle of sideslip, radians
δ_a	aileron deflection, radians
δ_r	rudder deflection, radians
ρ	air density, slugs/cu ft
σ	air density ratio
ϕ	angle of roll, radians
ψ	angle of yaw, radians

$$\omega_{\theta}^2 \quad \text{nondimensional pitch parameter,} \quad \left(-\frac{M_{\alpha}}{I_y} - \frac{M_q L_{\alpha}}{I_y m V} \right) / p^2$$

$$\omega_{\psi}^2 \quad \text{nondimensional yaw parameter,} \quad \left(\frac{N_{\beta}}{I_z} + \frac{N_r Y_{\beta}}{I_z m V} \right) / p^2$$

$$\left| \frac{\phi}{\beta} \right| \quad \text{ratio of roll angle to sideslip angle}$$

$$\left| \frac{\phi}{\psi} \right| \quad \text{ratio of roll angle to yaw angle}$$

$$\left| \frac{\phi}{v_e} \right| = \frac{57.3}{V} \frac{1}{\sqrt{\sigma}} \left| \frac{\phi}{\beta} \right|$$

$$C_{L_{\alpha}} = \frac{\partial C_L}{\partial \alpha}$$

$$C_{l_{\beta}} = \frac{\partial C_l}{\partial \beta}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$$

$$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r}$$

$$C_{m_{\alpha}} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{m_q} = \frac{\partial C_m}{\partial q}$$

$$C_{n_{\beta}} = \frac{\partial C_n}{\partial \beta}$$

$$(C_{n\beta})_{\text{dyn}} = C_{n\beta} - \frac{I_z}{I_x} \alpha C_{l\beta}$$

$$C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V}}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

$$C_{n\delta_a} = \frac{\partial C_n}{\partial \delta_a}$$

$$C_{n\delta_r} = \frac{\partial C_n}{\partial \delta_r}$$

$$C_{Y\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{Y\delta_r} = \frac{\partial C_Y}{\partial \delta_r}$$

$$L_\alpha = C_{L_\alpha} q S$$

$$M_\alpha = C_{m_\alpha} q S \bar{c}$$

$$M_q = C_{m_q} \frac{q S \bar{c}^2}{2V}$$

$$N_\beta = C_{n_\beta} q S b$$

$$N_r = C_{n_r} \frac{q S b^2}{2V}$$

$$Y_\beta = C_{Y_\beta} q S$$

Subscripts:

dyn dynamic

o value at angle of attack of zero

α denotes partial derivative with respect to angle of attack

ANALYSIS

Aircraft Flight Conditions and Characteristics

The lateral stability of the supersonic-transport configuration shown in figure 1 was investigated. The aircraft motion was represented with reference to the principal body axis by the linearized equations of lateral motion, as presented in reference 2. The gross weight was assumed to be 375,000 pounds. The flight conditions represented were for trimmed level flight at a Mach number of 3 at altitudes of 60,000 feet and 70,000 feet. The trim angle of attack at 60,000 feet was 3.6° and that for 70,000 feet was 5.8° with wing sweep angle of 75° . Calculations were made to determine the period and damping, the ratio of the roll angle to equivalent side velocity $\left| \frac{\phi}{v_e} \right|$, and the ratio of the roll angle to sideslip $\left| \frac{\phi}{\beta} \right|$ of the oscillating mode and the damping of the aperiodic modes. The aircraft-configuration characteristics and the conditions assumed for the flight evaluations are presented in table I.

For this variable-sweep configuration the wing-pivot station was considered a feasible center-of-gravity location, and pitching and yawing moments were referenced to the longitudinal location of the pivot point. For this center-of-gravity position the aircraft has a positive static margin ($C_{m_{CL}} = -0.233$). The stability derivatives were estimated from values computed according to the method of reference 3 and from wind-tunnel data of similar configurations. The contribution of an angle of attack to the stability derivatives C_{l_β} , C_{n_β} , and C_{n_p} is based on wind-tunnel test results, and the values are given in the appendix. A plot of $-C_{l_\beta}$ and C_{n_β} is presented in figure 2.

Flying Qualities

The problem of establishing flying-qualities requirements for the supersonic transport is being considered, but as yet no generally accepted requirements have been established. For the purpose of this analysis the satisfactory lateral-directional characteristics are accepted as those established for military aircraft, inasmuch as the present configurations should meet many of the requirements for the military aircraft. The Dutch roll mode is considered satisfactory for $\frac{1}{C_{1/2}} > 0.24$ with artificial dampers inoperative and for $\frac{1}{C_{1/2}} > 0.7$ with artificial dampers operating, as presented in reference 4 which includes the requirements of $\left| \frac{\phi}{v_e} \right|$. In addition, the criterion from reference 5 is imposed for the roll-to-sideslip ratio $\left| \frac{\phi}{\beta} \right| < 4$. Reference 5 stipulates a

satisfactory criterion for the roll-to-yaw ratio $\left(\left|\frac{\phi}{\psi}\right| < 4\right)$, in which roll and yaw motions are defined in the stability axis system. This criterion in some investigations has been applied to roll and sideslip motions, since $\left|\frac{\phi}{\psi}\right| \approx \left|\frac{\phi}{\beta}\right|$ in the stability axis system. The parameter $\left|\frac{\phi}{\beta}\right|$ is essentially independent of the axis system, and in this investigation (based on body axis equations of motion) the roll-to-yaw ratio criterion of reference 5 could be applied directly as a $\left|\frac{\phi}{\beta}\right|$ criterion. The criterion for the damping of the roll mode was selected from pilots' opinions as $\frac{1}{t_{1/2}} > 1$, and the criterion for the spiral mode was taken from reference 4 as $\frac{1}{t_2} < 0.05$. These criteria are used for reference values in this investigation, but further research to determine acceptable criteria is required for configurations of this type.

Stability Augmentation

For the purpose of this analysis, the aircraft stability was considered to be augmented by the inclusion of auxiliary dampers, which provided control-surface deflection proportional to rolling and yawing velocities. When the aircraft is augmented with auxiliary dampers, the cross-control effectiveness may have a destabilizing effect and should be considered in the analysis. Dampers were added to the basic configuration and were included as increments of damping in C_{l_p} and C_{n_r} , and the cross-control moments were added as increments in C_{n_p} and C_{l_r} by the use of the following equations:

$$\Delta C_{l_p} = \frac{2V}{b} k_1 C_{l_{\delta_a}}$$

$$\Delta C_{l_r} = \frac{2V}{b} k_2 C_{l_{\delta_r}}$$

$$\Delta C_{n_p} = \frac{2V}{b} k_1 C_{n_{\delta_a}}$$

$$\Delta C_{n_r} = \frac{2V}{b} k_2 C_{n_{\delta_r}}$$

where k_1 and k_2 are the roll- and yaw-damper gains $\delta_a/\dot{\phi}$ and $\delta_r/\dot{\psi}$, respectively.

RESULTS AND DISCUSSION

Unaugmented Configuration

Since some of the aerodynamic parameters vary appreciably with angle of attack, as indicated in figure 2, the basic configuration was analyzed to determine the effects of angle of attack on the lateral modes. Calculations were made for angle of attack varying from 0° to 10° , and account was taken of the variation in the static derivatives $C_{l\beta}$ and $C_{n\beta}$ and the rotary derivative C_{np} . Figure 3 shows the variation in the damping of the lateral modes and the period of the Dutch roll mode with angle of attack for altitudes of 60,000 feet and 70,000 feet. At an altitude of 60,000 feet, the damping of the roll mode decreases rapidly as α increases. Calculations show that at approximately $\alpha = 8^\circ$ the roll and spiral modes merge into a long-period oscillation. The period and damping of the Dutch roll mode increases gradually; this increase is attributed to a transfer of damping from the roll mode to the Dutch roll mode with an increase in α .

With an increase in the altitude to 70,000 feet the air density decreases and causes a decrease in the total damping. The period of the Dutch roll mode increases. The rate of change of damping of each mode with α maintains about the same trend as at 60,000 feet. The foregoing analysis indicates that, to fulfill the damping requirements and to establish satisfactory stability, augmentation of the basic configuration is necessary throughout the angle-of-attack range.

Effects of Roll and Yaw Dampers Without Cross-Control Moments

Effects of roll damper.— Figure 4(a) shows the variation in the damping of the lateral modes with an auxiliary roll damper k_1 with $C_{n\delta_a} = 0$. For an altitude of 60,000 feet and a trim angle of attack of 3.6° , the damping of the roll mode increases with k_1 and attains a satisfactory value for $k_1 \geq 0.52$, as shown by the satisfactory roll-mode boundary. The damping of the Dutch roll mode increases with k_1 because of the transfer of damping from the roll mode to the Dutch roll mode, as indicated previously, and becomes satisfactory for $k_1 \geq 0.20$, as shown by the satisfactory Dutch roll mode boundary. The damping of the spiral mode decreases as k_1 increases but remains stable throughout the k_1 range.

When the altitude is increased to 70,000 feet (fig. 4(a)), the diminution of the air density causes the total damping of the system to diminish, and an increase in the angle of attack for trim ($\alpha = 5.8^\circ$) causes the roll damper to act as a partial yaw damper. As k_1 increases, the damping of the roll mode increases gradually but is not sufficient to satisfy the flying-quality criterion. As a result of an increase in α , the damping of the Dutch roll mode has almost the same rate of increase as the damping of the roll mode and becomes

satisfactory for $k_1 \geq 0.19$. The damping of the spiral mode diminishes as k_1 increases but remains satisfactory throughout the k_1 range.

Effect of yaw damper.- The variation in the damping of the lateral modes with an auxiliary yaw damper k_2 with $C_{l\delta_r} = 0$ shows much the same trend as that due to an auxiliary roll damper. (See fig. 4(b).) At an altitude of 60,000 feet ($\alpha = 3.6^\circ$) the damping of the roll mode increases as k_2 increases. The damping of the Dutch roll mode, as expected, increases with k_2 and attains a satisfactory value for $k_2 \geq 0.15$. The damping of the spiral mode remains satisfactory as it increases with the yaw-damper gain.

At an altitude of 70,000 feet for which $\alpha = 5.8^\circ$ (fig. 4(b)), the increased α for trim causes the yaw damper to have more effect on the roll mode than on the Dutch roll mode. As k_2 increases, the rate of increase in the damping of the roll mode is greater than the rate of increase in the damping of the Dutch roll mode. In fact, at approximately $\alpha = 8^\circ$, k_2 no longer affects the Dutch roll damping. The damping of the roll mode is not sufficient, however, with any of the values of k_2 used in this analysis. The damping of the Dutch roll mode becomes satisfactory for $k_2 \geq 0.55$. The damping of the spiral mode obtains an initial increase with the increase in α at $k_2 = 0$ and continues to increase with k_2 at almost the same rate as the damping of the Dutch roll mode.

Effect of yaw and roll dampers.- For the purpose of determining the damper gains necessary for satisfactory damping of the lateral modes and of better evaluating the effects of the cross-control moment, values of k_1 were selected and calculations were made when k_2 was varied and when the cross-control moments $C_{n\delta_a}$ and $C_{l\delta_r}$ were neglected. Figure 5(a) shows the damping of the lateral modes for $h = 60,000$ feet and $\alpha = 3.6^\circ$ for two values of k_1 (0.35 and 0.50) and with k_2 varying from 0 to 0.5. For a value of $k_1 = 0.35$, the roll mode does not attain a satisfactory damping within the k_2 range. The damping of the Dutch roll mode is satisfactory for $k_2 = 0$, as a result of the roll-damper effects, and increases with k_2 . Increasing the roll-damper gain to $k_1 = 0.50$ causes the damping of the roll mode to attain a satisfactory value at $k_2 \geq 0.165$. The damping of the Dutch roll mode increases as a result of an increase in k_1 and continues to increase with k_2 so that a satisfactory value is maintained. The damping of the spiral mode decreases as k_1 increases but maintains a satisfactory value as k_2 increases.

Because of the decrease in the total damping with an increase in the altitude and the change in certain aerodynamic parameters with angle of attack, the roll-damper gain was increased with an increase in the altitude to 70,000 feet and a trim angle of attack of 5.8° . With roll-damper gains of 0.70 and 0.90 and with k_2 varying from 0 to 1.0 (fig. 5(b)), the damping of the roll mode

increases but does not attain a satisfactory value within the k_2 range. The damping of the Dutch roll mode is quite satisfactory for $k_2 = 0$ because of the amount of damping attributed to k_1 and the increases with k_2 at almost the same rate as the roll mode. The damping of the spiral mode decreases with increase in k_1 and increases with k_2 so that a satisfactory value is maintained.

Effects of Cross-Control Moments

The possible effects of the cross-control moments which occur when auxiliary dampers are added have been discussed in reference 2 and indicate the destabilizing effects that might occur in the Dutch roll and spiral modes. In view of these effects, the cross-control moments $C_{n\delta_a}$ and $C_{l\delta_r}$ were introduced into the analysis to determine the effects they would have on the stability. For the particular configuration and flight conditions of this investigation (table I), these values were $C_{n\delta_a} = -0.00464$ and $C_{l\delta_r} = 0.0056$.

Aileron cross-control effects.— For an altitude of 60,000 feet and an angle of attack of 3.6° , a comparison of figures 4(a) and 6(a) indicates that the aileron cross-control moment $C_{n\delta_a}$ causes a transfer of damping from the Dutch roll and spiral modes to the roll mode. The damping of the Dutch roll and spiral modes decreases as k_1 increases, and the damping of the roll mode increases as k_1 increases.

At an altitude of 70,000 feet and an angle of attack of 5.8° , the aileron cross-control moment becomes less effective because of the coupling effects of the roll and Dutch roll modes with an increase in angle of attack. Figure 6(a) shows that damping of the roll mode at $h = 70,000$ feet is satisfactory for $k_1 \geq 0.8$. The damping of the Dutch roll mode, although decreased because of $C_{n\delta_a}$, undergoes a slight increase as k_1 increases. However, at both altitudes the Dutch roll damping remains unsatisfactory for the range of k_1 considered. There is little or no effect on the damping of the spiral mode, which remains satisfactory, decreasing as k_1 increases.

Rudder cross-control effects.— A comparison of figures 4(b) and 6(b) shows that the rudder cross-control moment $C_{l\delta_r}$ causes a comparatively slight tendency to redistribute the damping to the Dutch roll and spiral modes as k_2 increases. Because of the coupling effects of the roll and Dutch roll modes with an increase in angle of attack, at an altitude of $h = 70,000$ feet and $\alpha = 5.8^\circ$ the damping of the roll and Dutch roll modes increases at almost the same rate with an increase in k_2 . The variation in the damping due to $C_{l\delta_r}$ is very small compared with the variation due to $C_{n\delta_a}$; therefore, values of k_2 larger than k_1 are indicated to offset the effects of $C_{n\delta_a}$.

Rudder and aileron cross-control effects.- For the purpose of evaluating the selected roll-damper gains for satisfactory damping of the lateral modes, the cross-control moments were included in the calculations and the yaw-damper gain was varied from 0 to 1.0. For an altitude of 60,000 feet with a roll-damper gain of $k_1 = 0.35$ (fig. 7(a)), the damping of the roll mode is satisfactory for $k_2 = 0$, because of the influence of $C_{n\delta_a}$, and increases with k_2 .

The damping of the Dutch roll mode decreases because of $C_{n\delta_a}$ but does increase with k_2 , and it attains a satisfactory value for $k_2 \geq 0.25$. If the damper gain is increased to $k_1 = 0.50$, the damping of the roll mode remains satisfactory and increases with k_2 . The damping of the Dutch roll and spiral modes decreases with an increase in k_1 but increases with k_2 , and the Dutch roll mode attains satisfactory damping for $k_2 > 0.30$.

For an altitude of 70,000 feet (fig. 7(b)) and a roll-damper gain of $k_1 = 0.70$, the damping of the roll mode attains a satisfactory value for $k_2 \geq 0.435$. The damping of the Dutch roll mode is satisfactory for $k_2 \geq 0.30$. When the damper gain is increased to $k_1 = 0.90$, the damping of the roll mode is satisfactory throughout the k_2 range. The damping of the Dutch roll mode, because of the coupling effects, now shows a moderate increase because of k_1 and attains a satisfactory value for $k_2 \geq 0.26$ with $k_1 = 0.9$. It should be noted that the rates of increase of the damping of both the roll and Dutch roll modes are almost equal.

Effects of Angle of Attack on Augmented Configuration

Some of the differences that occur at the different altitudes are related to the change in the angle of attack and can be seen in a plot of the damping of the lateral modes for the augmented configuration (i.e., the configuration with both roll and yaw dampers) as a function of α . For damper gains of $k_1 = 0.35$ and $k_2 = 0.50$ and with cross-control derivatives included (fig. 8), the damping of the roll mode, having satisfactory damping at $\alpha = 0^\circ$, decreases as α increases. The damping of the Dutch roll mode and spiral modes is also satisfactory at $\alpha = 0^\circ$ and increases with α .

If the yaw-damper gain is increased so that $k_2 = 0.70$, the damping of the roll mode is initially the same at $\alpha = 0^\circ$, decreases until $\alpha = 4^\circ$, then because of the coupling effects of the Dutch roll mode increases as α increases. The damping of the Dutch roll mode undergoes an initial increase at $\alpha = 0^\circ$ but begins to decrease at approximately $\alpha = 4^\circ$. At $\alpha > 9^\circ$ damping is less than the damping for the condition when $k_1 = 0.35$ and $k_2 = 0.50$. This condition at $\alpha > 9^\circ$ is also due to the coupling of the Dutch roll mode. The damping of the spiral mode undergoes an initial increase and continues to increase with α . When the roll-damper gain is increased so that $k_1 = 0.50$ and $k_2 = 0.50$, the damping of the roll mode increases at $\alpha = 0^\circ$ but decreases

rapidly as α increases. The damping of the Dutch roll and spiral modes decreases slightly at $\alpha = 0^\circ$ but increases rapidly as α increases because of the coupling of the roll modes.

Lateral-Directional Oscillation

The Dutch roll criterion of reference 4 is expressed in terms of damping required as a function of $\left| \frac{\phi}{v_e} \right|$, whereas it is suggested in reference 5 that large values of $\left| \frac{\phi}{\psi} \right|$ are intolerable, regardless of the damping. These criteria are inconsistent for high-altitude conditions, and for the purpose of this analysis both criteria are considered, inasmuch as it is recognized that $\left| \frac{\phi}{\psi} \right|$ in the stability axis system approximately equals $\left| \frac{\phi}{\beta} \right|$ in the body axis system. The boundaries for the satisfactory flying qualities of reference 4 are indicated in a plot of $\frac{1}{C_{l/2}}$ as a function of $\left| \frac{\phi}{v_e} \right|$. The roll-to-sideslip ratios are listed for comparison with the acceptable criterion of reference 5 which requires that $\left| \frac{\phi}{\psi} \right| < 4$. As shown in figure 9, the basic configuration ($k_1 = k_2 = 0$) and the configuration with the damper combinations which have been accepted as having satisfactory damping are in a region which provides tolerable or satisfactory Dutch roll oscillation for dampers inoperative and for dampers operating at 60,000 feet and 70,000 feet. (Note that the region labeled "tolerable" is considered satisfactory for operation without dampers.) The $\left| \frac{\phi}{\beta} \right|$ as tabulated for these conditions are considered unsatisfactory, however, since they do not meet the criterion that $\left| \frac{\phi}{\beta} \right| < 4$. Since the various damper combinations which would tend to reduce the values of $\left| \frac{\phi}{\beta} \right|$ would be considered rather large, the approximate expression of this ratio as presented in reference 6 was examined and an increase in $C_{n\beta}$ was considered. When $(C_{n\beta})_0$ is increased to 0.25 to give $C_{n\beta} = 0.1722$ at $h = 60,000$ feet and $C_{n\beta} = 0.1247$ at $h = 70,000$ feet (fig. 10), the basic configuration and the damper combinations still maintain satisfactory lateral-directional oscillations at both altitudes and have acceptable roll-to-sideslip ratios $\left| \frac{\phi}{\beta} \right|$.

Roll Coupling of the Undamped Configuration

For configurations with highly swept wings and low static stability, inertial coupling is often a problem, and hence a preliminary analysis of the roll-coupling characteristics of this configuration was undertaken. Critical rolling

velocities, as presented in reference 7, were calculated for three center-of-gravity positions (-6, 0, and 6 feet with respect to the wing-pivot location) and for altitudes of 60,000 and 70,000 feet and are presented in figures 11 and 12. The effect of this change was to change the values of $C_{m\alpha}$ and C_{np} , as shown in the appendix. For these calculations, the longitudinal and lateral modes of oscillation were arbitrarily assumed to have zero damping.

For a center-of-gravity location of $x_{cg} = 0$ at an altitude of 60,000 feet (fig. 11) the roll-coupling characteristics are considered unsatisfactory in the range $1.68 < p < 2.97$ where $\omega_{\psi}^2 < 0.8$ and $\omega_{\theta}^2 > 0.9$. Locating the center-of-gravity position aft of the wing-pivot point to $x_{cg} = 6$ feet decreases the upper boundary of the satisfactory range, with roll rates being unsatisfactory for $1.43 < p < 2.21$. Locating the center of gravity forward of the wing-pivot point to $x_{cg} = -6$ feet increases the upper boundary of the satisfactory range, with roll rates being unsatisfactory for $1.89 < p < 3.41$.

When the altitude is increased to 70,000 feet (fig. 12), the upper boundaries of roll rates for satisfactory roll-coupling characteristics are greatly reduced. For a center-of-gravity location of $x_{cg} = 0$, roll rates are unsatisfactory in the range $0.95 < p < 2.26$ where $\omega_{\psi}^2 < 0.8$ and $\omega_{\theta}^2 > 0.9$. When the center-of-gravity position is located forward of the wing-pivot point to $x_{cg} = -6$ feet, the roll rates are unsatisfactory for $1.17 < p < 2.69$.

It is evident that the roll-coupling characteristics are not the best to be desired in this configuration for the center-of-gravity locations presented. If consideration is given to an increase in the static directional derivative as a means of obtaining more favorable values of $\left| \frac{\phi}{\beta} \right|$, this increase could also be a contributing factor in obtaining better roll-coupling characteristics. If an increase in the static directional derivative, such as that in the section entitled "Lateral-Directional Oscillation," is considered ($C_{np} = 0.1722$ at an altitude of 60,000 feet), the critical rolling velocities are significantly increased and the unstable roll range is decreased. For a center-of-gravity location of $x_{cg} = 0$, the roll rates for satisfactory roll-coupling characteristics are unsatisfactory for $2.21 < p < 2.87$. When the center-of-gravity position is located forward of the wing-pivot point to $x_{cg} = -6$ feet, the roll rates are unsatisfactory for $2.38 < p < 3.41$. For an altitude of 70,000 feet and for $C_{np} = 0.1247$, roll rates are unsatisfactory in the range $1.48 < p < 2.26$ for a center-of-gravity location of $x_{cg} = 0$ and in the range $1.63 < p < 2.68$ for a center-of-gravity location of $x_{cg} = -6$ feet. It should be recognized that this analysis of the roll-coupling characteristics is a limited one. More detailed analysis should include the effect of damping on the critical velocity and should determine the transient motions to be encountered in rolling maneuvers.

CONCLUDING REMARKS

An investigation was made of the characteristic modes of the lateral stability for a variable-sweep-wing supersonic-transport configuration, cruising at a Mach number of 3 at altitudes of 60,000 and 70,000 feet with trim angles of attack of 3.6° and 5.8° , respectively. Calculations were based on the configuration at a gross weight of 375,000 pounds with a wing sweep angle of 75° .

Results show that augmentation by roll and yaw dampers is necessary for satisfactory lateral stability. With an increase in the altitude, the total aerodynamic damping of the system decreases and large increments in the damper gains are required. At the higher angle of attack required for flight at an altitude of 70,000 feet, coupling exists between the roll and Dutch roll modes to the extent that both roll damping and yaw damping have nearly equal influence on the roll and Dutch roll modes. Results also show that small values of the static-directional derivative causes unsatisfactory lateral-directional oscillations and contributes to roll-coupling problems. An increase in the static-directional derivative could improve these conditions.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 22, 1964.

APPENDIX

STABILITY DERIVATIVES AFFECTED BY ANGLE OF ATTACK AND CENTER-OF-GRAVITY POSITION

The stability derivatives affected by angle of attack are:

$$C_{l_\beta} = (C_{l_\beta})_o + (C_{l_\beta})_\alpha \alpha$$

$$C_{n_\beta} = (C_{n_\beta})_o + (C_{n_\beta})_\alpha \alpha$$

and

$$C_{n_p} = (C_{n_p})_o + (C_{n_p})_\alpha \alpha$$

Those derivatives affected by the center-of-gravity position are:

$$C_{n_\beta} = (C_{n_\beta})_o + C_{Y_\beta} \frac{x_{cg}}{b} + (C_{n_\beta})_\alpha \alpha$$

and

$$C_{m_\alpha} = C_{m_{C_L}} C_{L_\alpha} + C_{L_\alpha} \frac{x_{cg}}{\bar{c}}$$

The following values are used to solve the preceding equations:

$$(C_{l_\beta})_o = -0.063$$

$$(C_{n_p})_o = 0.023$$

$$(C_{l_\beta})_\alpha = -0.295$$

$$(C_{n_p})_\alpha = -0.108$$

$$(C_{n_\beta})_o = -0.177$$

$$C_{L_\alpha} = 1.550$$

$$(C_{n_\beta})_\alpha = -1.238$$

$$C_{m_{C_L}} = -0.233$$

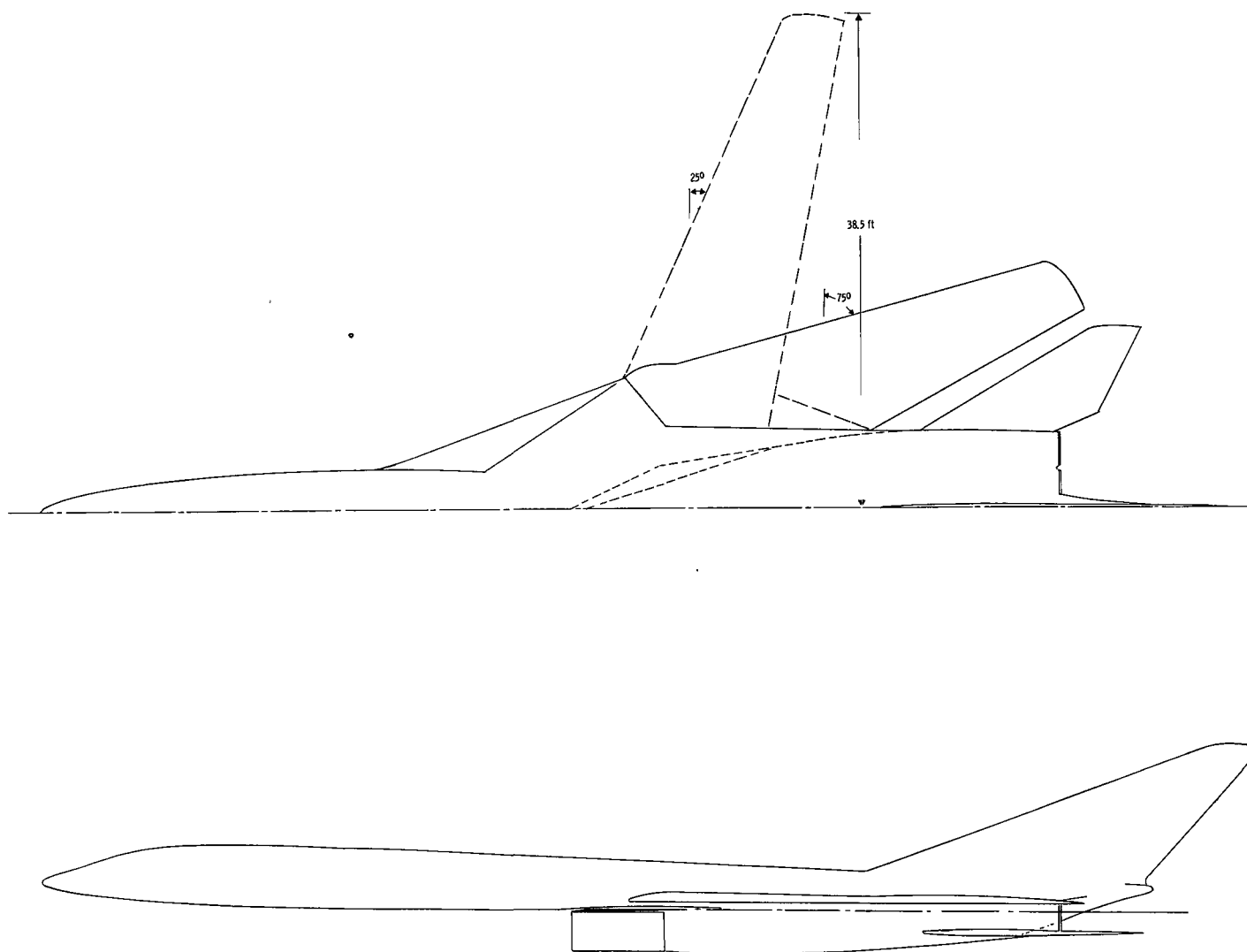
$$C_{Y_\beta} = -0.028$$

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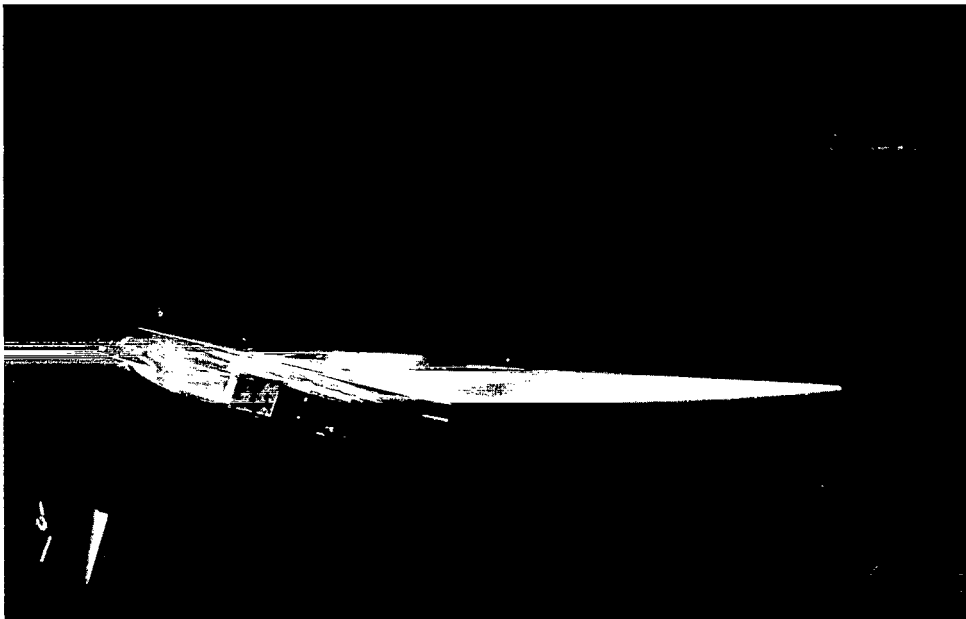
TABLE I.- CONFIGURATION CHARACTERISTICS AND FLIGHT CONDITIONS
USED FOR FLYING-QUALITIES EVALUATION

b, ft		77
\bar{c} , ft		63
I_x , (slugs)(sq ft)		1,484,000
I_y , (slugs)(sq ft)		11,784,000
I_z , (slugs)(sq ft)		13,112,000
m, slugs		11,650
S, sq ft		4,040
V, ft/sec		2,920
$C_{L\alpha}$		1.55
C_{l_p}		-0.124
C_{l_r}		0.1018
$C_{l\delta_a}$		-0.0055
$C_{l\delta_r}$		0.0056
C_{mC_L}		-0.233
C_{m_q}		-1.045
C_{n_r}		-0.453
$C_{n\delta_a}$		-0.00464
$C_{n\delta_r}$		-0.028
$C_{Y\beta}$		-0.347
$C_{Y\delta_r}$		-0.028
h, ft	60,000	70,000
q, lb/sq ft	953	590
α , deg	3.6	5.8
ρ , slug/cu ft	0.000223	0.000138
$C_{l\beta}$	-0.0815	-0.0929
$C_{n\beta}$	0.0992	0.0517
C_{n_p}	0.01621	0.0121

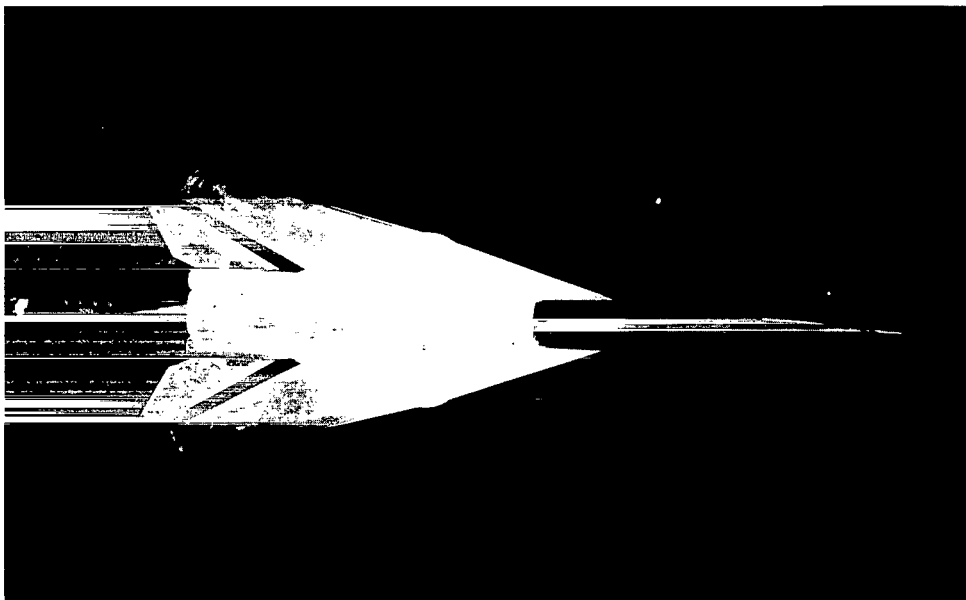


(a) Drawings of configuration.

Figure 1.- Profile and plan views of variable-sweep-wing supersonic-transport configuration used in this investigation.



L-63-2650



(b) Photographs of configuration.

L-63-2647

Figure 1.- Concluded.

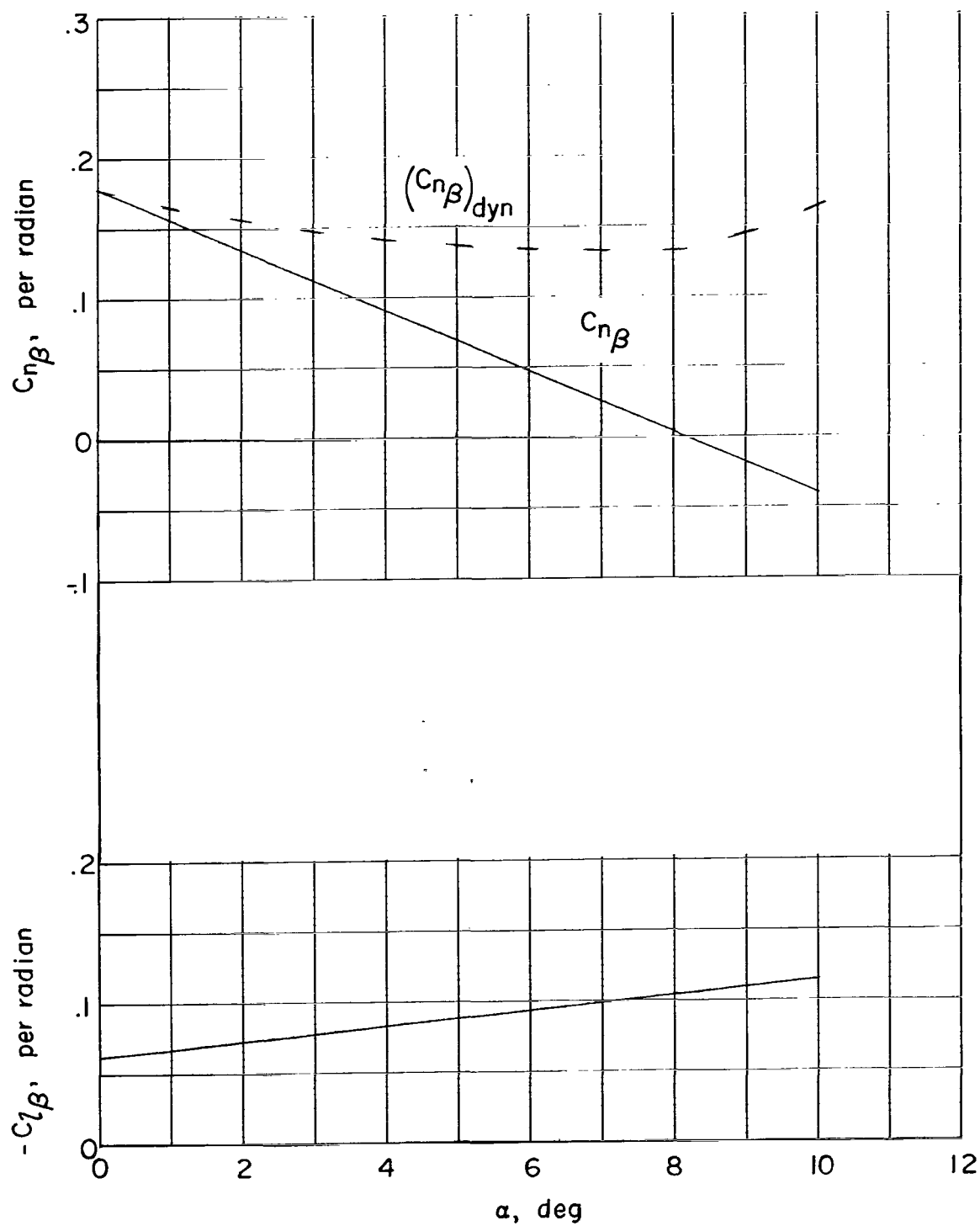


Figure 2.- Effect of angle of attack on stability derivatives $C_{l\beta}$ and $C_{n\beta}$.

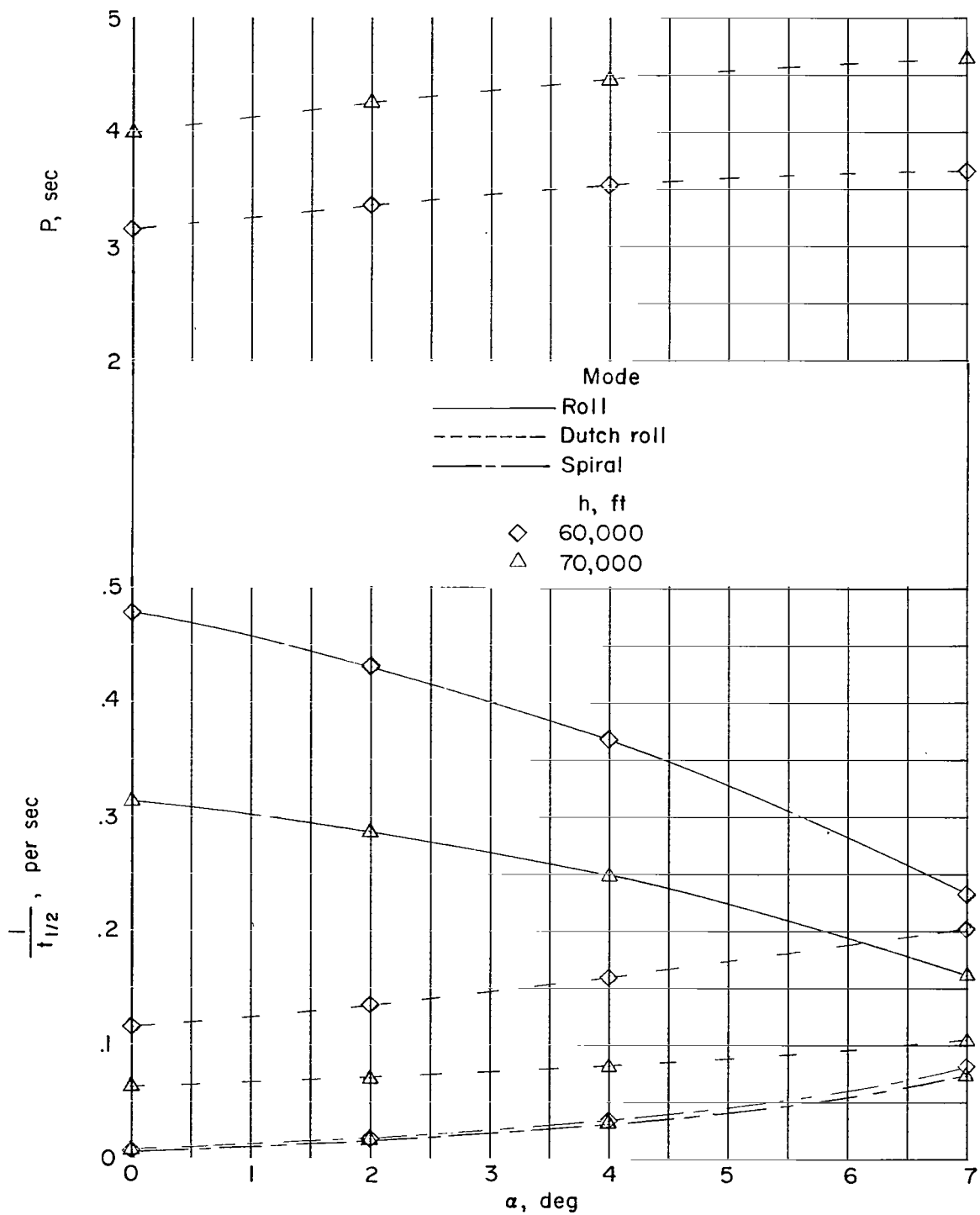
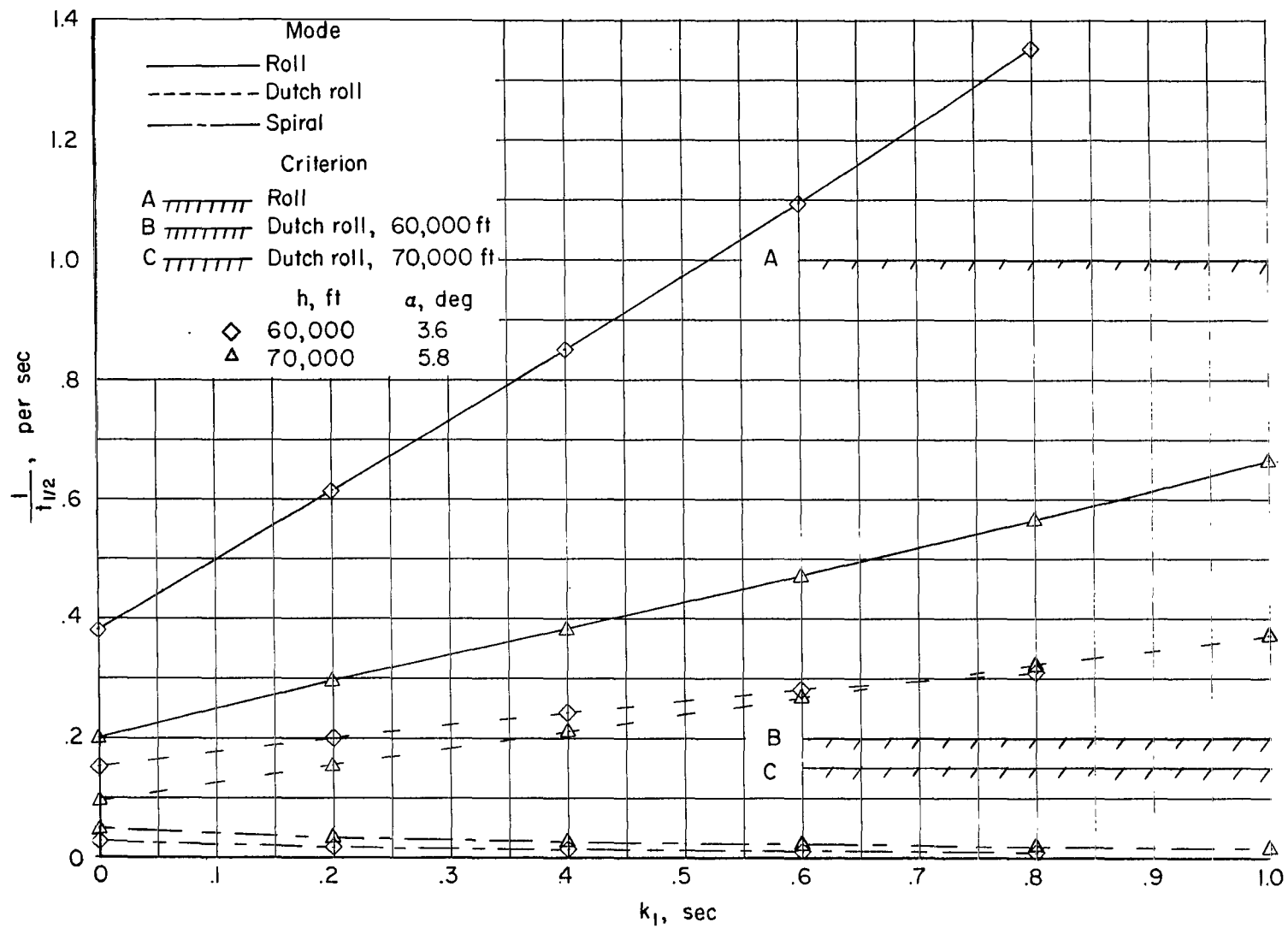
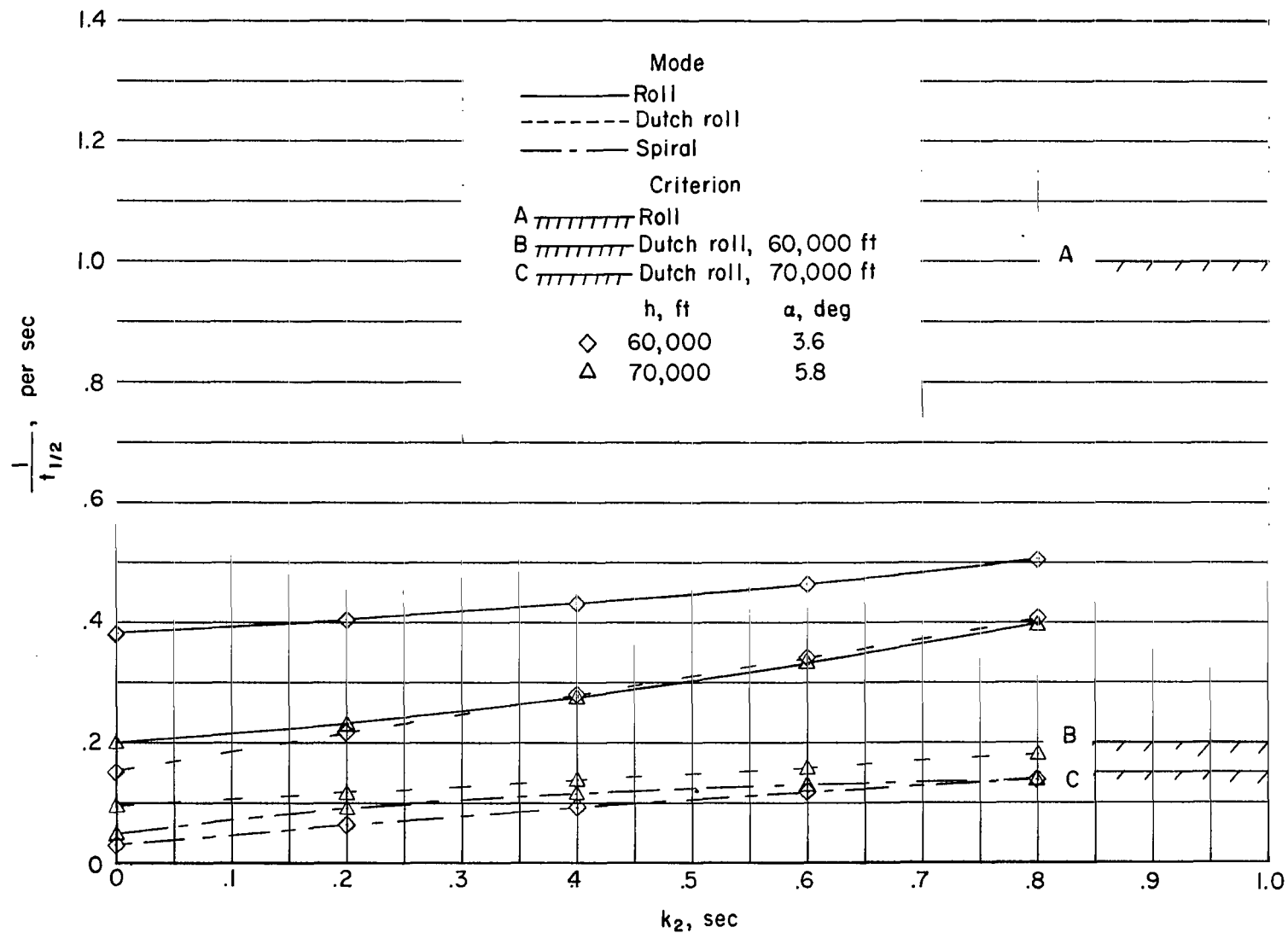


Figure 3.- Effect of angle of attack on period and damping of lateral modes.



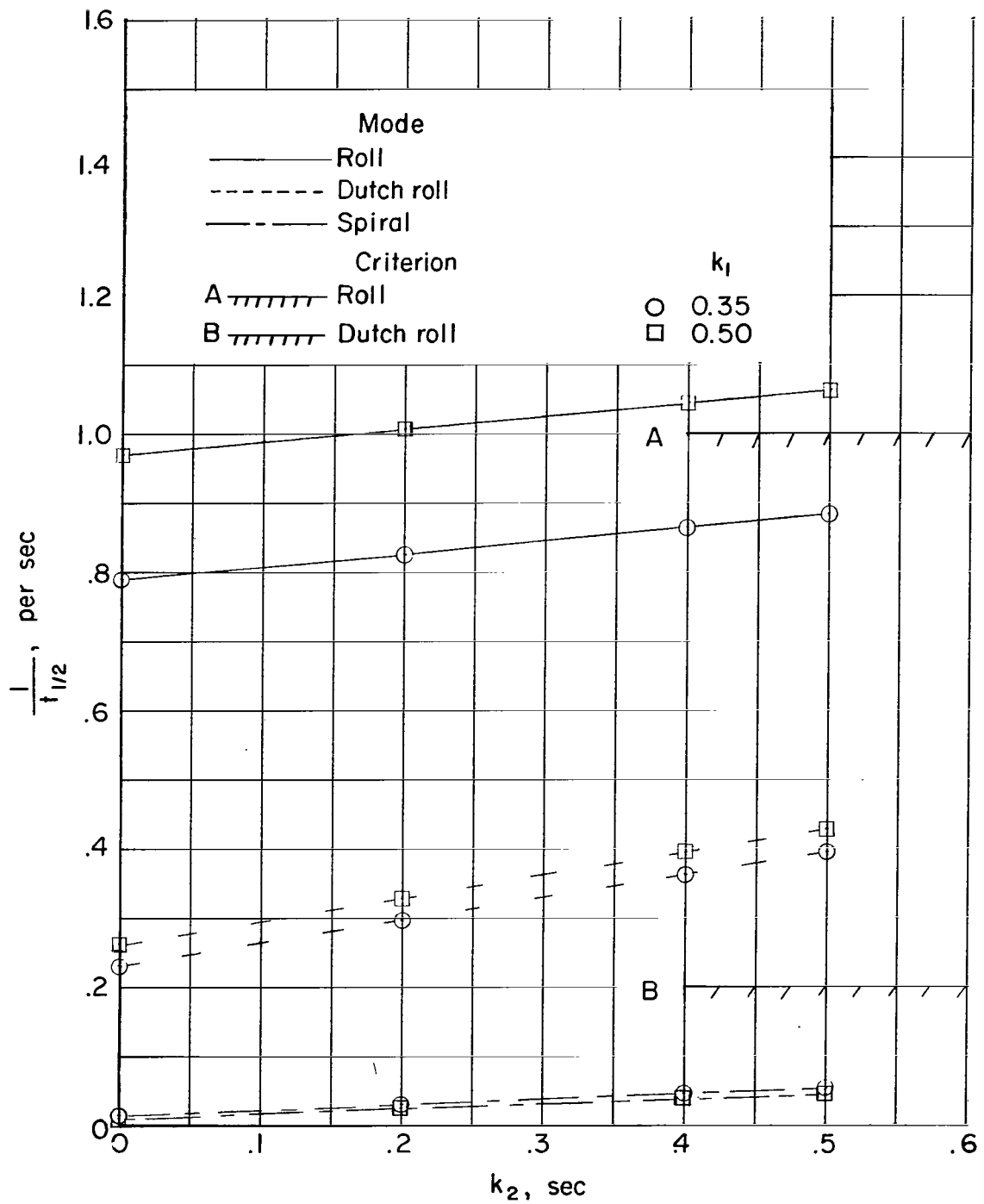
(a) Effects of roll-damper gains.

Figure 4.- Damping of lateral modes for no cross-control moments.



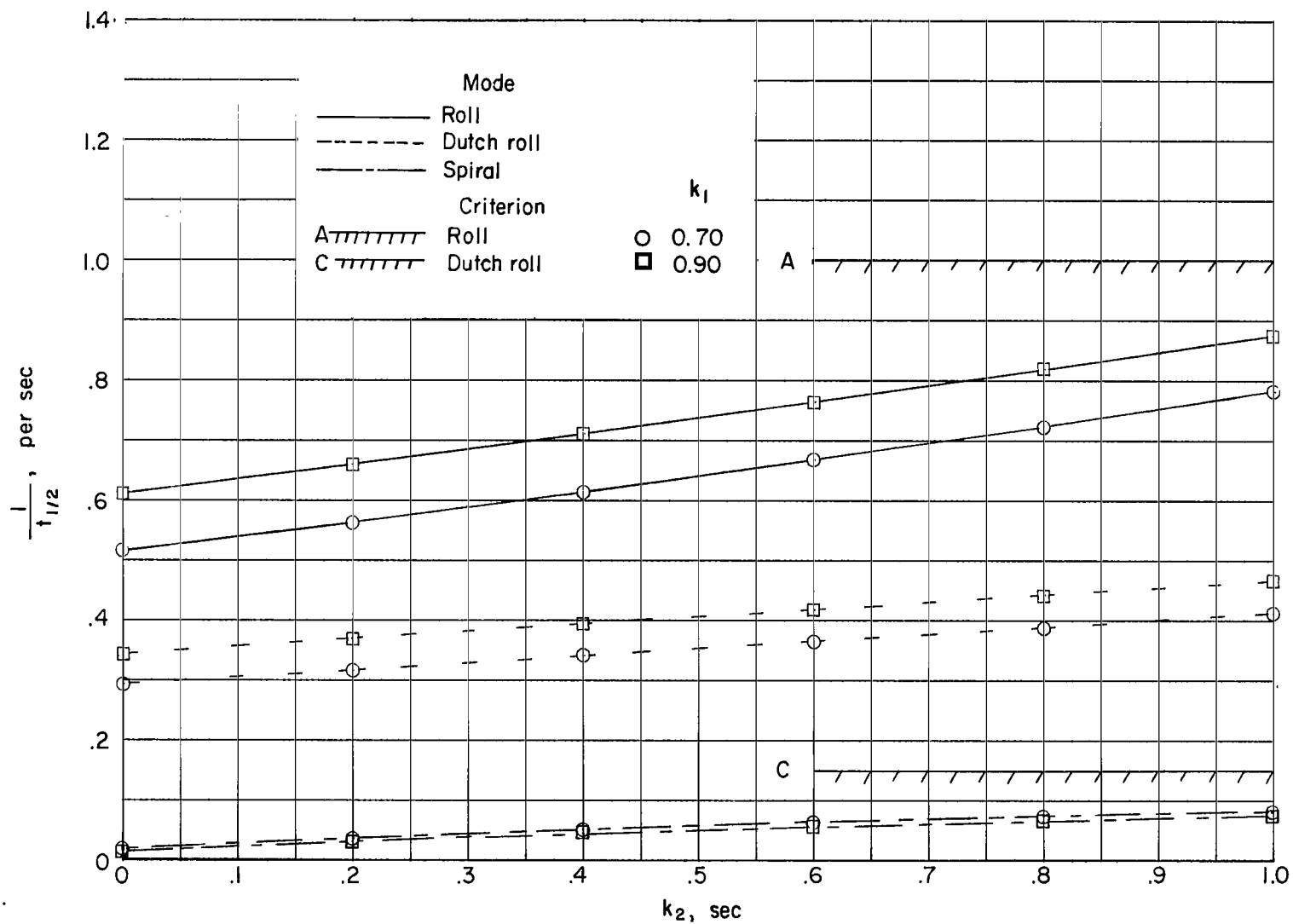
(b) Effects of yaw-damper gains.

Figure 4.- Concluded.



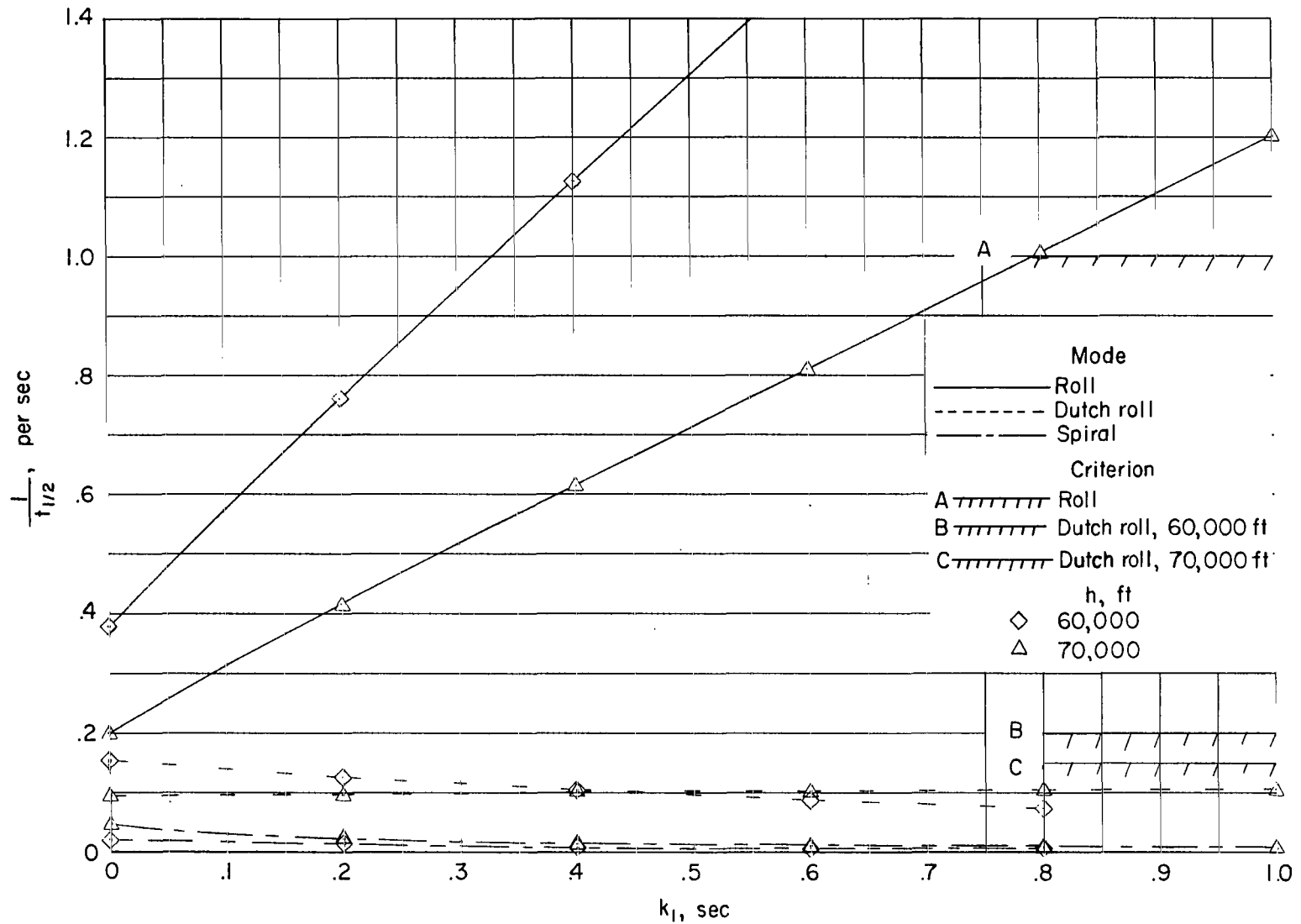
(a) Effects of yaw-damper gain at $h = 60,000$ feet and at $\alpha = 3.6^\circ$.

Figure 5.- Damping of lateral modes with no cross-control moments for given values of roll-damper gains.



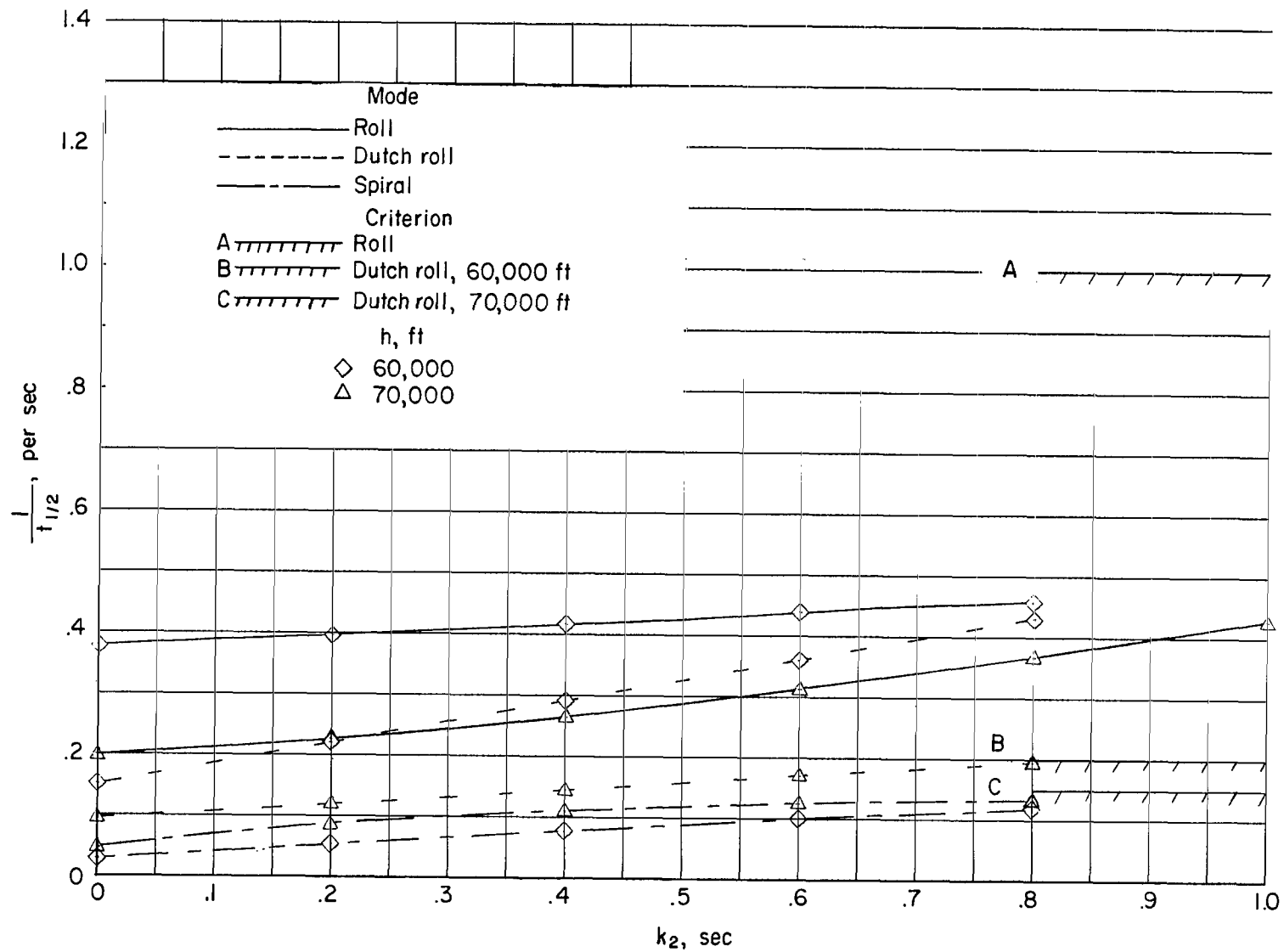
(b) Effects of yaw-damper gains at $h = 70,000$ feet and at $\alpha = 5.8^\circ$.

Figure 5.- Concluded.



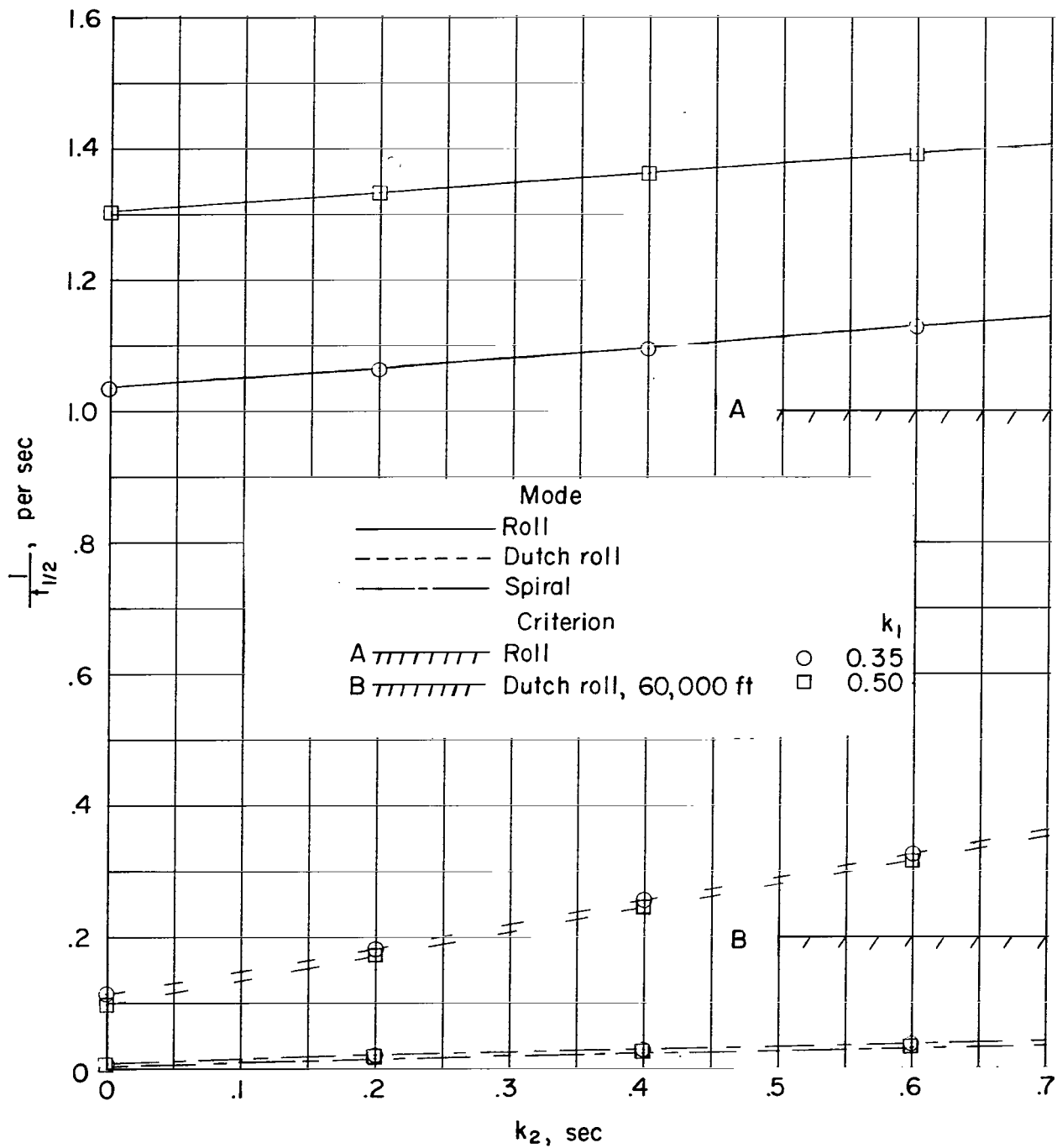
(a) Effects of roll-damper gains.

Figure 6.- Damping of lateral modes including cross-control effects.



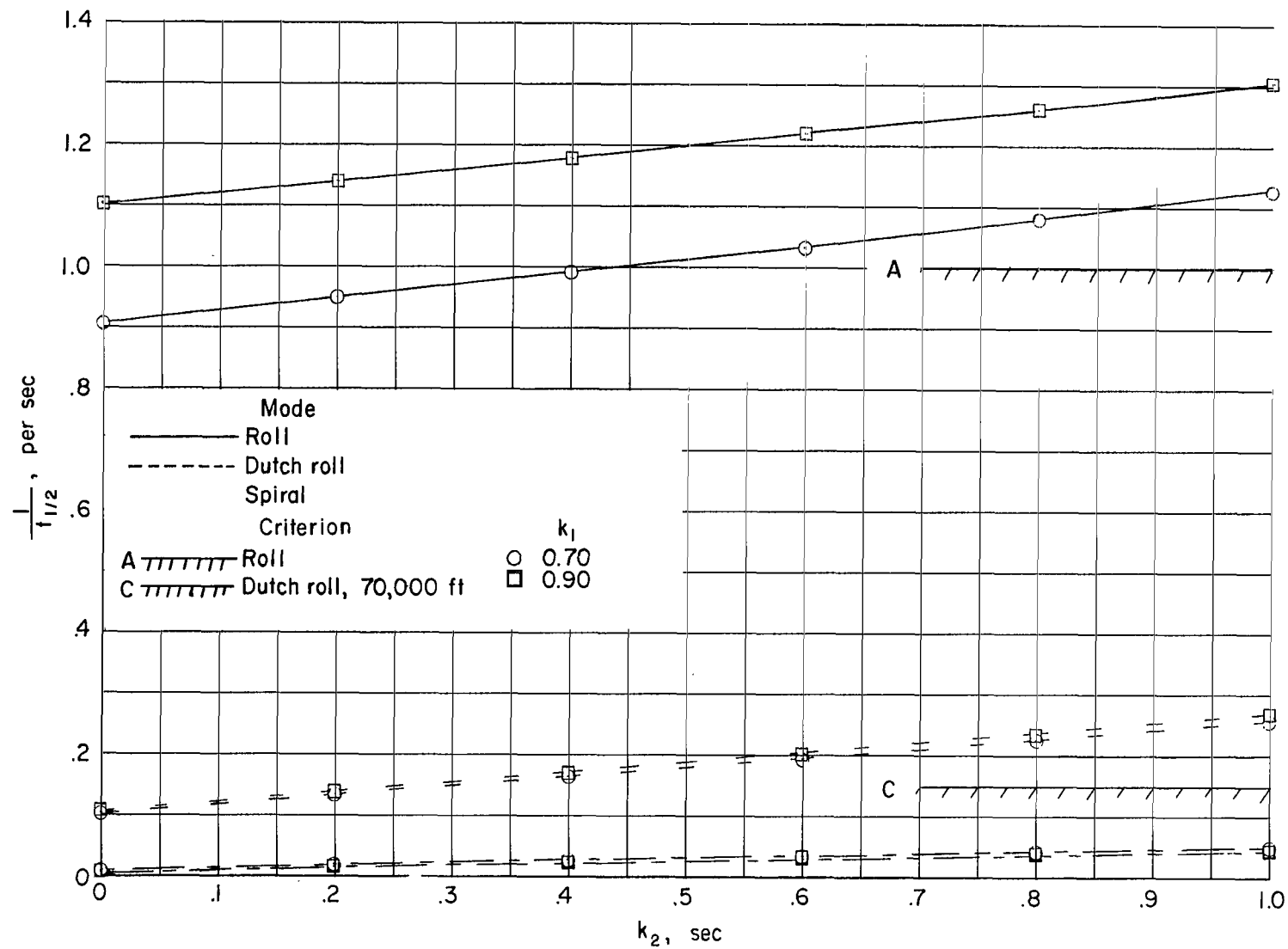
(b) Effects of yaw-damper gains.

Figure 6.- Concluded.



(a) Effects of yaw-damper gains at $h = 60,000$ feet and at $\alpha = 3.6^\circ$.

Figure 7.- Damping of lateral modes for roll and yaw dampers including cross-control moments.



(b) Effects of yaw-damper gains at $h = 70,000$ feet and at $\alpha = 5.8^\circ$.

Figure 7.- Concluded.

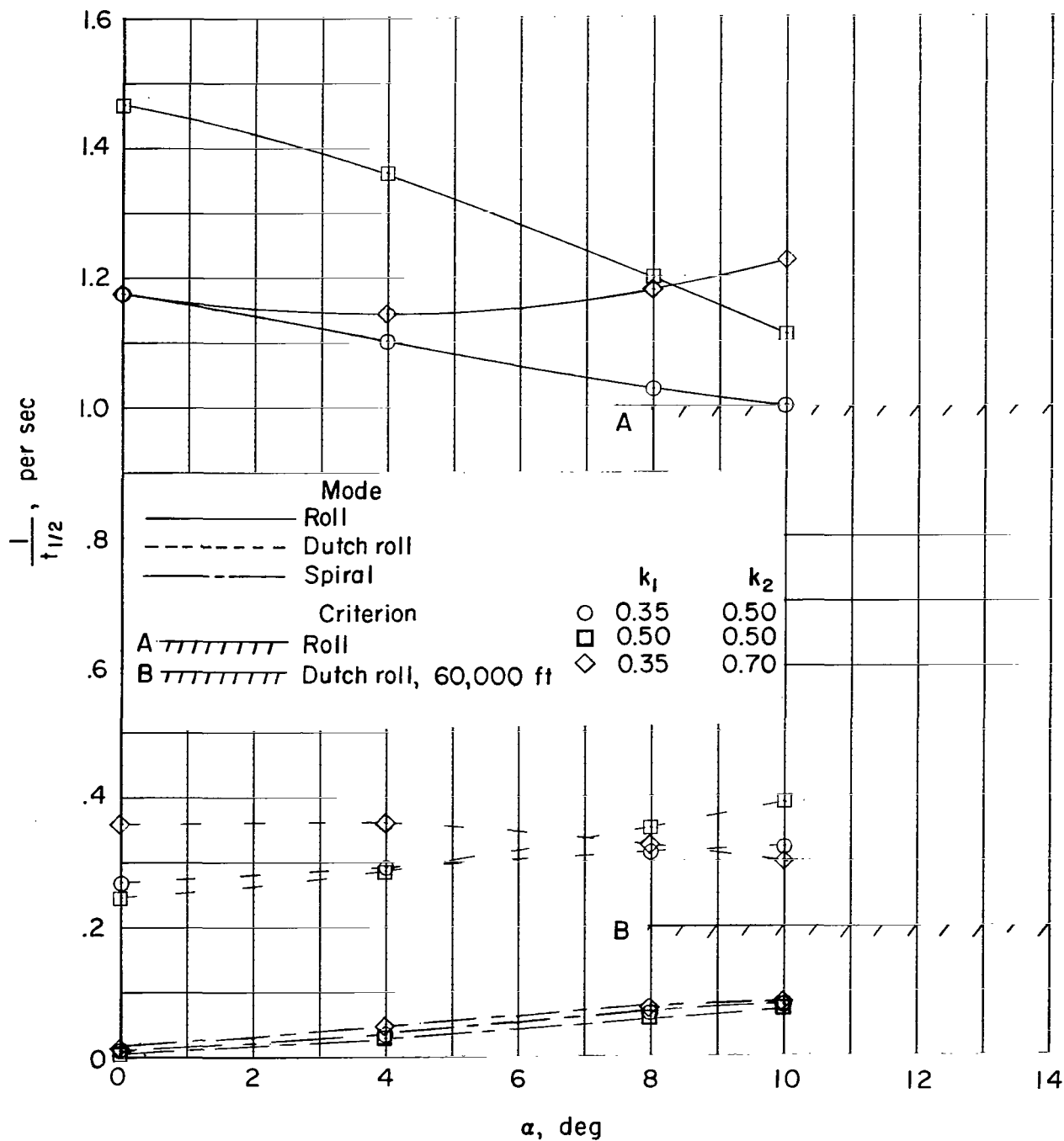


Figure 8.- Effects of angle of attack on damping of lateral modes at an altitude of 60,000 feet with roll and yaw dampers.

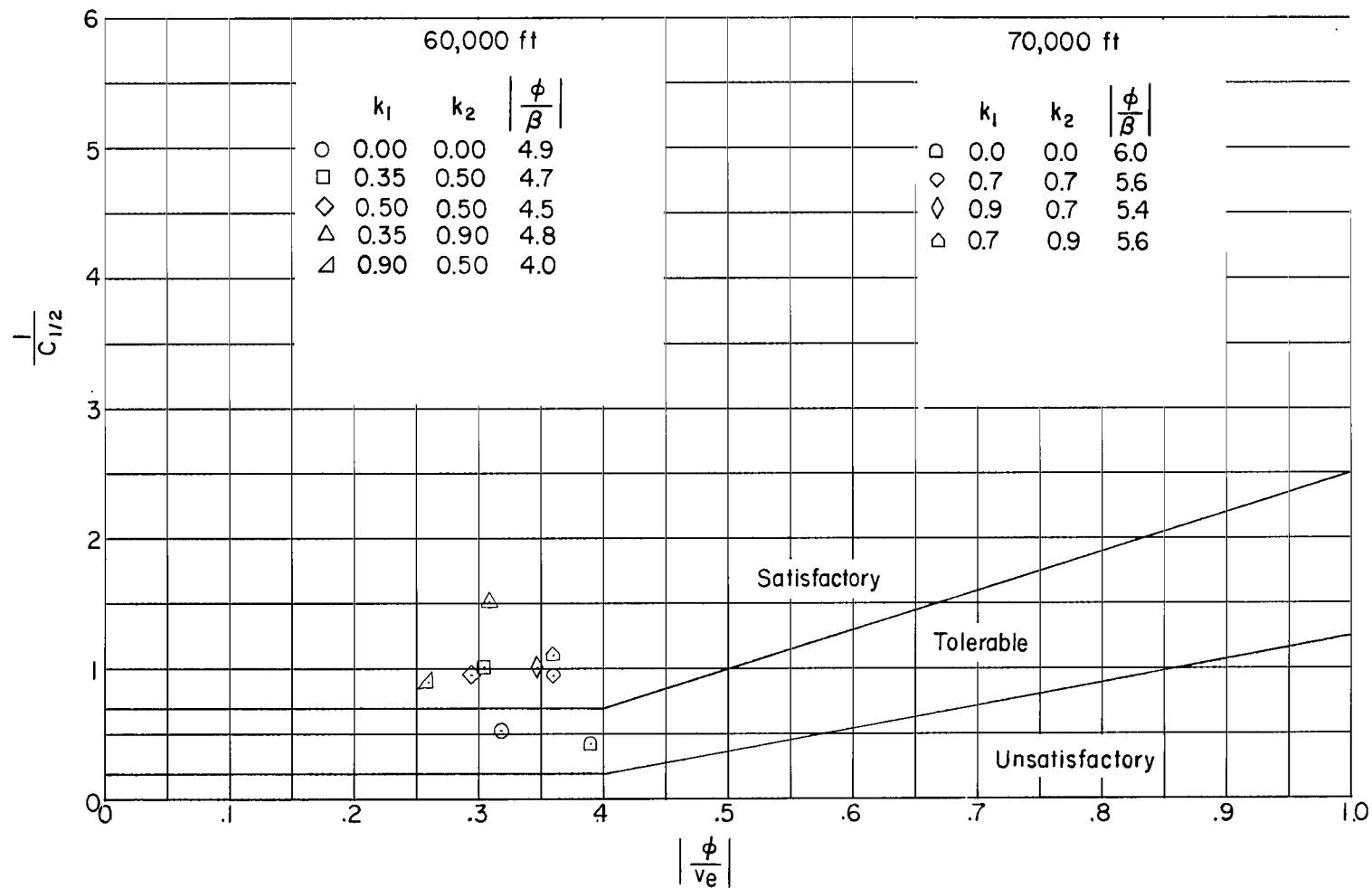


Figure 9.- Lateral-directional oscillation for undamped and damped configurations at altitudes of 60,000 and 70,000 feet.

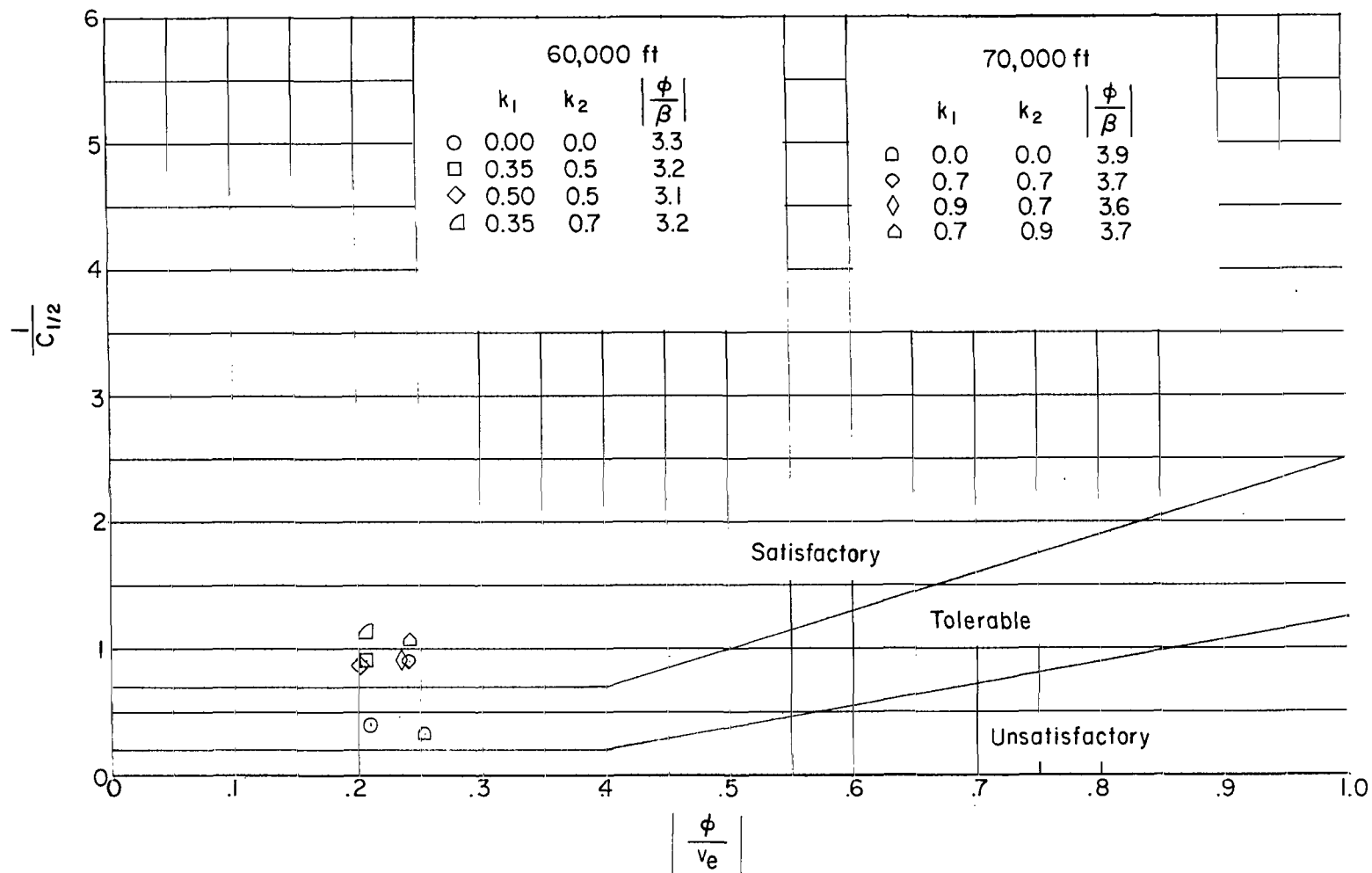


Figure 10.- Lateral-directional oscillation for undamped and damped configurations with increase in $C_{n\beta}$ at altitudes of 60,000 and 70,000 feet.

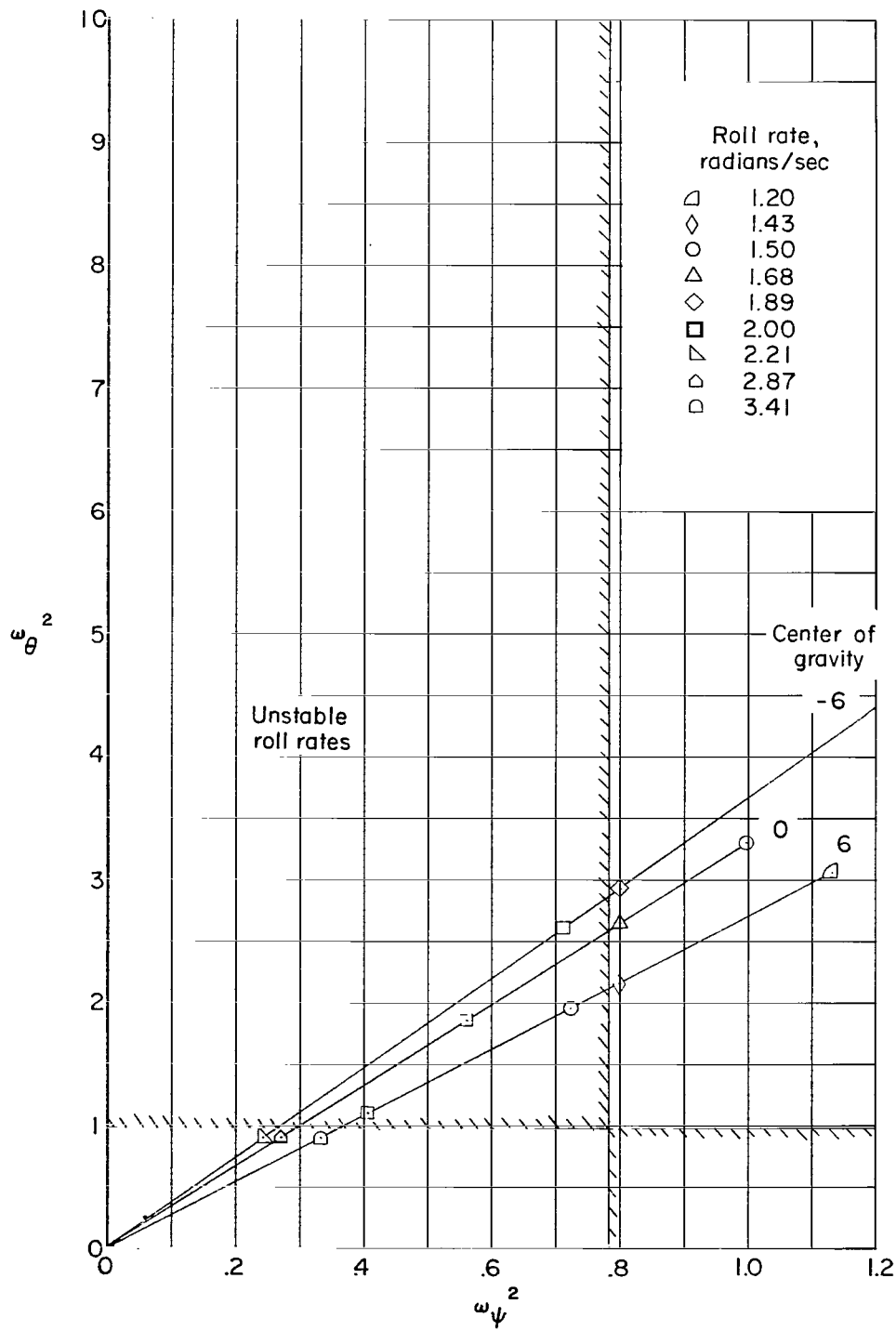


Figure 11.- Roll-coupling stability boundary for three center-of-gravity positions of undamped configuration at an altitude of 60,000 feet and at an angle of attack of 6° .

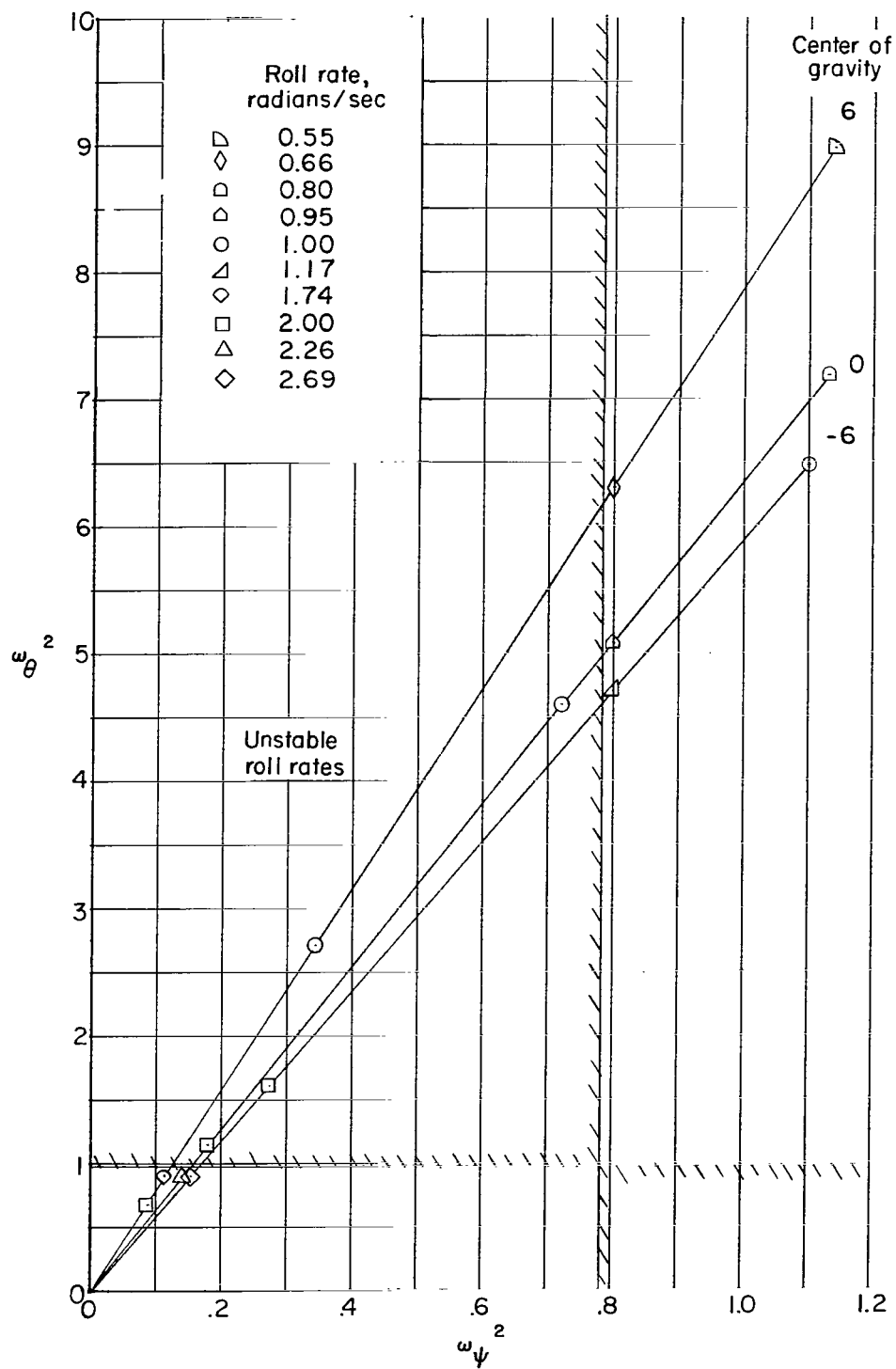


Figure 12.- Roll-coupling stability boundary for three center-of-gravity positions of undamped configuration at an altitude of 70,000 feet and at an angle of attack of 5.8° .

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D.

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